

3

Environmental Systems: Chemistry, Energy, and Ecosystems

Chapter Objectives

This chapter will help students:

- Describe the nature of environmental systems
- Explain and apply the fundamentals of environmental chemistry
- Describe the molecular building blocks of organisms
- Differentiate among the types of energy and recite the basics of energy flow
- Distinguish photosynthesis from respiration, and summarize their importance to living things
- Define ecosystems and evaluate how living and nonliving entities interact in ecosystem-level ecology
- Outline the fundamentals of landscape ecology
- Compare and contrast how carbon, phosphorus, nitrogen, and water cycle through the environment

Lecture Outline

I. Central Case: The Gulf of Mexico's "Dead Zone"

- A. In 2002, the dead zone grew to its largest size ever—22,000 square km (8,500 square miles).

- B. The dead zone is a region in the Gulf of Mexico so depleted of oxygen that it cannot support marine organisms, a condition called **hypoxia**.
- C. Scientists studying the dead zone have determined that fertilizer runoff from Midwestern farms is a major cause.

II. Earth's Environmental Systems

- 1. Our planet's environment consists of complex networks of interlinked systems.
 - 2. The interactions of living organisms with each other and with the environment
 - 3. The cycles of chemical elements and compounds
- A. Systems involve feedback loops.
- 1. A system is a network of relationships among a group of parts, elements, or components that interact with and influence one another through the exchange of energy, matter, and/or information.
 - 2. Systems receive input, process it, and produce output.
 - 3. Sometimes a system's output can serve as input to that same system in a circular process called a **feedback loop**.
 - a. In a **negative feedback loop**, output driving the system in one direction acts as input that moves the system in the other direction.
 - b. In a **positive feedback loop**, the output drives the system further toward one extreme.
- B. Environmental systems interact
- 1. Scientists divide Earth's major components into structural spheres
 - a. The **lithosphere** is the rock and soil beneath our feet.
 - b. The **atmosphere** is composed of the air surrounding us.
 - c. The **hydrosphere** encompasses all water—fresh and salt, liquid, ice, or vapor.
 - d. The **biosphere** consists of all living organisms and the abiotic (nonliving) parts of the environment with which they interact.
- C. Understanding the dead zone requires considering the Mississippi River and Gulf of Mexico systems together.

1. The cause of hypoxia in the Gulf of Mexico stems from excess nitrogen and phosphorus from the Mississippi River *watershed*.
2. Excess nutrients are present in runoff from fertilized agricultural fields, animal manure, crop residues, sewage, and industrial and automobile emissions.
3. The nutrients reach the Gulf where they boost the growth of microorganisms; this provides food for bacterial decomposers, which flourish.
4. The decomposers use the oxygen in the water; other organisms, such as fish and shrimp, suffocate and die.
5. The process of nutrient enrichment, algal bloom, bacterial increase and ecosystem deterioration is called **eutrophication**.

III. Chemistry and the Environment

1. Examine many environmental issues, and you will likely discover chemistry playing a central role; chemistry is also central to developing solutions.
- A. Atoms and elements are chemical building blocks.
1. An **element** is a fundamental type of matter that cannot be broken down into substances with other properties.
 2. Elements are composed of **atoms**, the smallest component of an element that maintains the chemical properties of that element.
 3. Every atom has a nucleus of **protons** (positively charged particles) and **neutrons** (particles lacking electric charge); the *atomic number* of the element is the number of protons each atom contains, and the *mass number* is the combined number of protons and neutrons.
 4. An atom's nucleus is surrounded by negatively charged particles known as **electrons**, which balance the positive charge of the protons.
 5. Although all the atoms of an element have the same atomic number and the same number of protons, they may not contain the same number of neutrons; these are called **isotopes**, and they have different mass numbers.
 6. Because isotopes differ slightly in mass, they also differ slightly in their behavior; researchers have used this to study many phenomena both in and out of the lab.

7. Some isotopes shed subatomic particles (decay) and emit high-energy radiation as they do so; they are called *radioisotopes*, and are radioactive.
8. Each radioisotope decays at a particular rate, called the *half-life*, or the amount of time it takes for one-half the atoms to give off radiation and decay.
9. Atoms may also gain or lose electrons to become **ions**, which are electrically charged. An ion may consist of a single charged atom or be a combination of two or more atoms from one or more elements.

B. Atoms bond to form molecules and compounds.

1. Atoms can bond together in chemical reactions to form **molecules**, combinations of two or more atoms.
2. If atoms in a molecule are composed of two or more different elements, the molecule is called a **compound**.
3. Atoms bond together in molecules due to attraction for one another's electrons.
 - a. When atoms in a molecule share electrons, they have a *covalent bond*.
 - b. If one atom exerts a greater pull, then one or more electrons may be transferred from an atom of one element to an atom of another element; this creates two oppositely charged ions and forms an *ionic bond*.
 - c. These associations of ions are called *ionic compounds*, or *salts*.
4. Elements, molecules, and compounds can come together without chemical bonding in a substance called a mixture.
 - a. Homogenous mixtures of substances are called *solutions*, which are often used for liquids but can also apply to some gases and solids.

C. Hydrogen ions determine acidity.

1. Water molecules occasionally dissociate, forming a hydrogen ion (H^+) and a hydroxide ion (OH^-).
2. Solutions in which the H^+ concentration is greater than the OH^- concentration are **acidic**, while solutions in which the OH^- concentration is greater than the H^+ concentration are **basic**.

3. The **pH** scale was devised to quantify the acidity or basicity of solutions, and runs from 0 to 14, with 0 to 6 being acidic, 7 being neutral, and between 8 and 14 being basic.

D. Matter is composed of organic and inorganic compounds.

1. **Organic compounds** consist of carbon atoms (and generally hydrogen atoms) and are joined together by covalent bonds.
2. **Hydrocarbons** only contain atoms of carbon and hydrogen.

E. Macromolecules are building blocks of life.

1. *Polymers* are long chains of repeated molecules, and three polymers—proteins, nucleic acids, and carbohydrates—play key roles as building blocks of life.
2. Lipids are not considered polymers but are also fundamental to life; these four types of molecules—proteins, nucleic acids, carbohydrates, and lipids—are referred to as **macromolecules** because of their large size.
3. **Proteins** are made up of long chains of *amino acids*. Proteins provide structure, transport substances, defend against invaders, carry messages, and promote certain chemical reactions.
4. **Nucleic acids** are molecules that direct the production of proteins.
 - a. There are two nucleic acids—**deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**—that carry the hereditary information for organisms and are responsible for passing traits from parents to offspring.
 - b. Nucleic acids are long strands of nucleotides. A nucleotide contains a sugar molecule, a phosphate molecule, and a nitrogenous base.
 - c. Deoxyribonucleic acid (DNA) has four types of nucleotides and can be pictured as a ladder twisted into a spiral.
5. **Carbohydrates** are organic compounds consisting of carbon, hydrogen, and oxygen atoms in the ratio of about 1 carbon to 2 hydrogen to 1 oxygen; they are used for energy (simple sugars) and to build structures such as leaves, lobster shells, and fingernails (polysaccharides).
6. **Lipids** are a fourth type of macromolecule, but are not polymers, and do not dissolve in water; they include fats, phospholipids, waxes, and steroids. Lipids are used for energy storage, membranes, and hormones.

F. Organisms use cells to compartmentalize macromolecules.

1. All living things are composed of **cells**, the most basic unit of organization.
2. Biologists classify organisms into two groups based on the structure of their cells.
 - a. *Eukaryotes* have cells with organelles (internal structures that perform specific functions), including a nucleus.
 - b. *Prokaryotes* are generally single-celled and lack organelles and a nucleus.

IV. Energy Fundamentals

1. **Energy** can change the position, physical composition, or temperature of matter.
 2. There are two fundamental types of energy:
 - a. **Potential energy** is the energy of position.
 - b. **Kinetic energy** is the energy of motion.
 3. **Chemical energy** is a special type of potential energy that is held in the bonds between atoms.
- A. Energy is always conserved, but it changes in quality
1. The **first law of thermodynamics** states that energy can change from one form to another, but cannot be created or lost.
- B. . . . But energy changes in quality.
1. The **second law of thermodynamics** states that energy tends to change from a more-ordered state to a less-ordered state, if no force counteracts this tendency.
 2. The less-ordered or disordered state of a system is called *entropy*. Entropy can also be seen as a loss of organization in a system.
- C. Light energy from the sun powers most living systems.
1. The sun supplies energy to those organisms that are able to use it to produce their own food; they are **autotrophs**, or primary **producers**.
 2. Autotrophs turn light energy from the sun into chemical energy in a process called **photosynthesis**.

3. In photosynthesis, sunlight powers a series of chemical reactions that convert water and carbon dioxide into sugars and oxygen, providing high-quality energy that the organism can use.
4. Photosynthesis produces food for plants and animals.

D. **Cellular respiration** releases chemical energy.

1. The chemical energy created by photosynthesis can later be used by organisms in the process of cellular respiration.
2. Cells use the reactivity of oxygen to convert glucose back into its original starting materials, water and carbon dioxide, and release energy to perform tasks within cells.
3. This extraction of energy occurs in both autotrophs and **heterotrophs**, or **consumers**.

V. **Ecosystems**

1. An **ecosystem** consists of all interacting organisms and abiotic factors that occur in a particular place at the same time.
2. Ecosystems that physically abut each other may interact extensively.
 - a. An *ecotone* is a transitional zone where two or more ecosystems meet and where some elements from each ecosystem mix.

A. Energy flows and matter cycles through ecosystems

1. Scientists recognize that biological entities are intertwined with chemical and physical entities.
2. Ecosystems receive inputs of energy, process and transform that energy and cycle matter internally.
3. Ecosystems process outputs (heat, water flow, and wastes) that can move into other ecosystems.

B. Energy is converted to biomass.

1. Energy flow in most ecosystems begins with the sun.
2. Autotrophs capture the sun's energy through photosynthesis. This is *gross primary production*.
3. After autotrophs use some of their acquired energy for their own metabolism, the remainder is used to generate biomass. This amount is the **net primary production**.

4. The rate at which biomass is generated is called *productivity*. Ecosystems with rapid biomass production have high **net primary productivity**.

C. Nutrients can limit ecosystem productivity.

1. **Nutrients** are elements and compounds that organisms consume and require for survival. Availability of nutrients is often a limiting factor for autotroph production.
2. In natural ecosystems, some nutrients always run off land into oceans. This nutrient input causes high primary productivity in nearshore waters along continents.
3. Increased nutrient pollution from farms, cities, and industry has increased the number of dead zones across the globe.

D. **Landscape ecologists** study geographic patterns.

1. We can conceptualize ecosystems at different scales.
2. **Landscape ecology** is the broad-scale study of geographical areas that include multiple ecosystems, and scientists studying at this level examine how landscape structure affects abundance, distribution, and interactions of organisms.

VI. Biogeochemical Cycles

A. Nutrients circulate in **biogeochemical cycles**.

B. The **carbon cycle** circulates a vital organic nutrient.

1. The **carbon cycle** describes the routes carbon atoms take through the environment.
2. Through photosynthesis, producers pull carbon dioxide out of the atmosphere to produce oxygen and carbohydrates.
3. During cellular respiration, producers, consumers, and decomposers break down carbohydrates to produce carbon dioxide and water.
4. Humans are shifting carbon from the lithosphere to the atmosphere.
 - a. As we mine fossil fuel deposits and cut or burn vegetation, we remove carbon from reservoirs and increase the flux into the atmosphere.
 - b. This ongoing flux of carbon into the atmosphere is a major force behind global climate change.

C. The phosphorus cycle involves mainly lithosphere and ocean.

1. The **phosphorus cycle** has no appreciable atmospheric component.
2. Phosphorus is primarily found in rocks, soil, sediments, and oceans; the weathering of rocks releases phosphates into water at a very low rate of flux.
3. Concentrations of available phosphorus in the environment are very low; it is often a limiting factor for producers.
4. Humans influence the phosphorus cycle.
 - a. We mine rocks for phosphorus to make fertilizers, and our sewage discharge agricultural runoff is high in phosphates.
 - b. These additions to the available reservoir of phosphorus in water and soil can cause rapid increases in algal growth, and eutrophication and hypoxia in waterways.

D. The nitrogen cycle involves specialized bacteria.

1. Nitrogen makes up 78% of the atmosphere and is the sixth most abundant element on Earth.
2. The **nitrogen cycle** involves chemically inert nitrogen gas that most living organisms cannot use. This makes the atmosphere the major reservoir for nitrogen.
3. Lightning, highly specialized bacteria, and human technology are the only ways to fix nitrogen into compounds usable by living organisms.
4. Nitrogen is frequently a limiting factor for producers, and therefore limits populations of consumers, including humans.
5. There are two ways that inert nitrogen gas becomes “fixed” so that plants can use it: nitrogen fixation and nitrification.
 - a. **Nitrogen fixation** occurs through lightning or **nitrogen-fixing bacteria** that live in mutualistic relationships with many leguminous plants.
 - b. **Nitrification** occurs through specialized free-living bacteria.
6. Decomposers release nitrogen as ammonium ions that are converted to nitrates and nitrites by **denitrifying bacteria**.

E. Humans have greatly influenced the nitrogen cycle.

1. Nitrogen fixation has always been a *bottleneck*, limiting the flux of nitrogen out of the atmospheric reservoir.
2. Use of synthetic nitrogen-based fertilizers is accelerating flux of nitrogen into other reservoirs within the cycle.
3. Burning forests and fields and fossil fuels all increase the amount of atmospheric nitrogen, as does bacterial decomposition of animal wastes from feedlots.
4. Scientists, farmers, and policymakers are examining strategies to limit the amount of damage caused by excess nutrients in the waterways that alleviate pollution while not hurting agriculture.

F. The **hydrologic cycle** influences all other cycles.

1. The oceans are the main reservoir, holding 97% of all water on Earth. Less than 1% of planetary water is usable by humans.
2. Water moves into the atmosphere via **evaporation** and **transpiration**. It returns to the surface as **precipitation**, most of which flows into water bodies as **runoff**.
3. Some precipitation and surface water soaks down to recharge underground reservoirs known as **aquifers**. This is **groundwater**, and the upper limit of this water in an aquifer is the **water table**. Groundwater reservoirs can remain unchanged for thousands of years, and can take additional thousands of years to recharge.
4. Human activity has affected every aspect of the water cycle.
 - a. We have dammed rivers and created reservoirs, increasing evaporation and, in some cases, infiltration.
 - b. We have changed vegetation patterns, increasing runoff and erosion and decreasing recharge.
 - c. Irrigation, industry, and other human uses have depleted aquifers and increased evaporation.
 - d. Atmospheric pollutants have changed the chemical nature of precipitation.

VII. Conclusion

1. Understanding the biogeochemical cycles that describe the movement of nutrients within and among ecosystems is crucial, as human activities are changing how these cycles function.

2. Deciphering how organisms function and interact depends in part on understanding energy, energy flow, and chemistry.
3. Approaching questions holistically by taking a systems approach is needed to understand the Earth's processes to avoid disruption of cycles.
4. The case of the Gulf of Mexico's hypoxic zone provides evidence that systems thinking can lead the way to solutions.